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THE DESIGN AND APPLICATION OF AN INFRARED SIMULATOR FOR THERMAL VACUUM TESTING

Douglas J. Skinner,[a] Steven P. Wallin,[b] and Calvin M. Wolff[a]

ABSTRACT

An infrared simulator was developed and installed in Chamber A in support of the Apollo lunar-exploration mission thermal vacuum testing. The simulator was designed to provide thermal simulation of the radiation emitted and reflected by the lunar surface incident on the Apollo service module in a 60-mile-altitude lunar orbit. The infrared simulator comprises 18 individually controlled zones that provide the irradiance profiles over a 180° arc around the spacecraft, simulating the flux levels of equatorial, polar, and 45° lunar orbits.

INTRODUCTION

An extensive design and development program was initiated to provide a large infrared (IR) simulator for the thermal vacuum testing of the Apollo scientific instrument module (SIM). The primary design requirements are as follows.

1. Isotropic (diffuse) IR flux must be provided over a 180° arc around the Apollo service module to simulate the directionality of lunar thermal emission. The isotropicity is necessary because some critical components recessed in the (SIM) reflective cavity are sensitive to directionality and because many of the critical surfaces are not diffuse absorbers.

2. The flux must be controllable independently in 18 evenly spaced heater zones parallel to the axis of the service module to achieve the various orbital flux profiles.

3. The color temperature must not exceed 600° F and should match that portion of the lunar surface corresponding to each heater zone; that is, the product of the vehicle-to-simulator view factor and the hemispherical emittance should be as close to

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[a]Brown & Root-Northrop, Houston, Texas.

[b]NASA Manned Spacecraft Center, Houston, Texas.

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unity as possible because of numerous critical heat-transfer surfaces having varying IR absorption spectra.

4. The thermal response time must be minimized to allow controllability for each heater zone to simulate transient flux conditions.

5. The flux range at the spacecraft surface must be controllable from 140 to 440 Btu/ft^2-hr for each heater zone.

6. The system must be compatible with the existing 6-bit binary input, 12-kilowatt, and 117- or 208-volt proportional power controllers.

The final configuration of the IR simulator is a retractable, semicylindrical envelope located opposite the solar simulation array. The power to each heater zone was controlled to a predetermined profile to provide a transient circumferential flux profile equivalent to that experienced in a 60-mile-altitude lunar orbit. For lunar darkside simulation, the simulator was retracted so that the spacecraft could view the liquid-nitrogen-cooled chamber paneling.

The mechanical design, the thermal design (including the special preparation of the heater strips), the control system, and the calibration of the IR simulator are described.

MECHANICAL DESIGN

Cage Structure

The IR simulator is a semicylindrical envelope with 18 heater zones positioned 18 inches from the spacecraft at a diameter of 16 feet with an overall height of 18 feet (Figs. 1 and 2). These heater zones are mounted in a cage structure, which is composed of an inner support frame and a concentric outer structural member. The four equally spaced support and structural members are connected by self-adjusting cross braces. The outer structural member with the slotted cross braces provides for the expansion and contraction of the cage while providing structural rigidity. The inner and outer sections are 17 feet 4 inches and 21 feet 4 inches in diameter, respectively. The entire structure was fabricated from 2-inch o.d., 0.188-inch wall, 6061-T6 aluminum tubing. The total weight of the structure, including heater zones and power cabling, is 1900 pounds.

Because of the high operating temperature of the heater strips and the exposure of the cage structure to the liquid-nitrogen-cooled cryogenic panels, the inner and outer frame would experience large temperature gradients (approximately 460° F at the center of the simulator). This condition necessitated a thermal stress analysis of the entire structure. The digital computer program, "STRAN," was used to calculate the forces, bending moments, and deflections caused by the expected temperature gradients. The maximum compressive and tensile stresses were calculated to be 13 220 psi and 12 780 psi, respectively, and provided a safety factor in excess of 3.0.

Support Structure

The support structure comprises a vertical truss and support arm structure, double-hinged upper lifting booms, and cross-braced stabilizer booms (Figs. 1 and 2). The vertical truss support arm and upper lifting booms were fabricated from 6-inch-wide flange H-beams of 6061-T6 aluminum. Two-inch o.d., 0.125-inch wall aluminum tubing was used for the stabilizer booms. All bearings and pivot pins were 300 series stainless steel. The structural analysis of the IR simulator support system indicated stresses $<10\ 000$ psi, which provided a safety factor of 3.5 for the stainless steel components and slightly >3.0 for the aluminum members.

Infrared Simulator Heater Zone

A typical IR simulator heater zone is presented in Figure 3. The zone is composed of four 208-inch-long high-purity 80-percent nickel, 20-percent chromium strips 3.75 inches wide and 0.006 inch thick. The strips were connected in series with a copper bus at the top and bottom; and the zone temperature was controlled by the average of 6 to 12 thermocouple readings, depending on zone location. Several thermocouples were installed on the back side of the heater strips to provide control and the temperature gradient over the entire length of the strip. The special high-response copper-constantan thermocouple installation is shown in Figure 4. This attachment provided good thermal contact and fast response time with the heater but was electrically isolated from the strip. The electrical-mechanical details are illustrated in Figure 5. As shown, the four heater strips were spaced 1/4 inch apart with glass-filled Teflon spacers, which were bolted on the back side of the heater strips by self-locking stainless steel nuts and bolts. A 1/16-inch copper strip was installed between the heater strip and the Teflon spacer to decrease the possibility of localized hot spots. The glass-filled Teflon spacers were selected after several candidate materials were evaluated for mechanical integrity under temperature extremes of -320° to +450° F. The 1/8-inch-thick copper bus sections also were bolted to the heater strips with stainless steel self-locking nuts and bolts. Again, this assembly was selected after several techniques (silver soldering, brazing, etc.) had been evaluated. Two 4-inch-long stainless steel springs were installed at the bottom of the heater-zone assembly and were adjusted to provide a 100-pound tension preload at ambient temperatures. This assembly ensured a flat heater zone under temperature extremes from full power (320° F) to cold-soak (-150° F) temperatures.

Chamber A Installation

The installation of the IR simulator in Chamber A at the NASA Manned Spacecraft Center (MSC) is shown in Figures 1 and 2. The IR cage structure is supported by a 1/2-inch-diameter stainless steel lift cable and the vertical truss structure. The cage is cantilevered on two 264-inch-long lifting booms. A box-section hinge system was designed for the cage end of the booms, which were spring loaded to provide positive positioning of the cage during retraction and redeployment.

To achieve the near-zero flux levels corresponding to the dark side of the moon, the simulator had to be lifted above the SIM bay to allow the spacecraft to view the liquid-nitrogen-cooled cryogenic panels. After a thorough review of several mechanisms, a parallelogram lift system was selected. This system provides excellent repeatability of precise positioning of the IR simulator around the spacecraft. A plan view of the IR simulator deployed at a distance of 18 inches around the spacecraft is shown in Figure 1.

Lift Mechanism

The IR simulator cage structure was automatically retracted by a 1/2-inch cable and winch-motor assembly, which was installed at an elevation of approximately 65 feet. (See Fig. 1.) The drive system comprises a 1.5-horsepower, 3-phase, 208-volt motor connected to an 80:1-ratio gearbox. The entire drive system, including the magnetic brake, was enclosed in a vacuum-tight housing. The housing is pressurized to 30 psia with dry nitrogen. Controlled heaters are installed to maintain the components at essentially ambient temperature. The output shaft of the gearbox is connected to the drum through a vacuum feedthrough. The lift mechanism was designed to fully retract the IR simulator in less than 1 minute. In addition to the magnetic brake, the support-arm pads also provided a positive stop during the lowering of the IR simulator.

THERMAL DESIGN

Heat Source

Three types of flux-generating systems were investigated:

1. Quartz-tungsten IR lamps with reflectors
2. Film heaters embedded in Kapton and mounted on 1/16-inch-thick, black-painted aluminum sheet
3. Directly excited, very thin nickel-chromium alloy sheets

The IR lamps were rejected because of their inability to meet the isotropicity requirement and also because of their very high color temperature (>1000° F, and variable, depending on the power input). The film heater on an aluminum sheet was rejected, after laboratory testing, because of the slow thermal response (300° to 0° F in 15 minutes, 0° to 300° F plateau in 10 minutes) and the danger of outgassing (of heater and adhesive) of condensable materials upon heater failure. Also, because of the large area of the simulator required (approximately 500 ft^2), the heater cost was high, approximately $\$50/ft^2$. The directly excited, thin nickel-chromium strips met the requirements when painted with a high-emissivity coating. This material proved to be ideal because its high mechanical strength permitted physical integrity of very thin strips and because its relatively high resistance permitted high-voltage, low-current operation. The thin strips have a very large surface-to-thermal-mass ratio, which provides the fast thermal response.

For compatibility with the existing 6-bit binary input, 12-kilowatt, 117- or 208-volt proportional controllers and for provision of the optimum view factor from the test article, each simulator zone consisted of four parallel vertical strips 17 feet long, 3-3/4 inches wide, and 0.006 inch thick. The strips were connected electrically in series. To minimize arcing (corona), the 120-volt mode of the power controllers was employed. Use of this mode required a resistance of 1.5 ohms, which corresponded to a maximum power input of 8×10^3 watts/zone. Several material and fabrication problems had to be solved prior to the final design of the system. The final selection of materials and fabrication techniques are discussed in some detail herein.

Heater-Strip Material

The material selected was a high-purity "Tophet A" alloy, 80-percent nickel, 20-percent chromium, and essentially iron free. The resistivity of this material is 510 ohms/mil foot at 20° C, with deviation ranging from -0.7 to +6 percent in the range -60° to +400° F.

Thermocouples

Copper-constantan thermocouples embedded in Kapton film were selected to provide fast thermal response and electrical isolation from the heater strips. The embedded thermocouples were applied with Minnesota Mining and Manufacturing Company (3M) no. 467 adhesive transfer tape. (See Fig. 4.) The Kapton film has been shown to be unaffected by operation at temperatures up to 500° F. The thin thermocouple foil and thin (approximately 1 mil) Kapton film caused negligible temperature differential between the thermocouple and the heater strip. The thin material also has a very small thermal mass and, thus, permits the thermocouple to closely follow the variation in the heater-strip temperatures.

Heater-Strip Insulation

The electrical insulation and heater-strip spacers were Teflon with 25-percent-glass filler. Wherever Teflon was to be placed over the heater strip, copper was attached first to the strip to create an electrical short over the covered area and, thereby, to prevent excessive temperatures caused by inhibition of heat dissipation by the Teflon.

Heater-Strip Coating

An extensive evaluation of several materials was made before the 3M Nextel 401C-10 black velvet paint was selected. Some of the coatings that were tested and rejected are the following.

1. Potassium silicate black - This coating, developed at the NASA Goddard Space Flight Center by Schutt, was the most promising because it was of higher emittance than any other coating evaluated; because it is electrically insulating; and because it is inorganic, which is highly desirable from a contamination standpoint. Unfortunately, the material did not adhere well enough to the nickel-chromium alloy to be acceptable. The problem areas were around nonmetallic parts (insulators, spacers, thermocouples), which seemed to be centers about which the

coating would blister and eventually flake off. The alloy was degreased and given a final bath in hot 3-percent hydrogen peroxide to 1-percent ammonia solution to provide as clean a surface as possible. The surface was also "broken," before cleaning, with fine grit emery cloth. This paint, however, adhered very well to aluminum and to sandblasted nickel-chromium alloy. The 6-mil-thick alloy, however, was so thin that it severely warped upon sandblasting; therefore, such pretreatment was unacceptable.

2. Magna X-500 - This is a low-outgassing urethane, flat-black material that is electrically conductive. The material adhered well to the nickel-chromium alloy, but its emittance was approximately 6 percent less than that of the 3M black velvet paint. The electrical conductivity was not desirable because of the danger of shorting between the strips, which were only 1/4 inch apart.

3. Plasma-jet-applied ceramic coatings - Emittances of these coatings were lower than emittances of coatings mentioned previously, and all ceramic coatings required sandblasting for adherence.

The method developed for applying the 3M paint to the nickel-chromium strip is as follows.

1. Surface preparation

a. Place full-length heater strips on workbench covered with clean polyethylene film.

b. Clean strips with precision-grade Freon, using paper wipes. Clean gloves (polyethylene or other plastic) are to be worn for this and following operations.

c. Prepare a solution of two parts of water and one part of Dupont 57175 metal conditioner. Apply the solution to the strips with a brush or sponge, and scrub surfaces with 220- to 280-grit sandpaper or steel wool until the glaze is removed. Keep the surface wet with the solution during the deglazing operation.

d. Wipe off all the solution from the surface, using a clean, dry cloth; and let the surface dry for 10 minutes.

e. Assemble heater strips with other parts to form individual IR simulator heater zone. (See Fig. 3.) Mount the entire assembly in a special handling fixture.

f. Apply thermocouples (copper-constantan embedded in Kapton film), using 3M no. 467 adhesive transfer tape as a bonding material. Using a lamp, heat the thermocouples to 160° F for 5 minutes. While heating, press the thermocouple to remove all air bubbles.

g. Wipe off heater surfaces with methyl ethyl ketone.

2. Priming

a. Prime the heater surfaces with 3M Nextel 901C primer, and air flash for 3 to 5 minutes. Priming and coating are to be done along the long dimension. Use a spray gun for the operation.

b. Air dry for 5 to 7 minutes before proceeding to the next step.

3. Coating and drying

a. Prepare 3M 401C-10 Nextel black velvet paint according to the manufacturer's specifications.

b. Spray a thin coat, followed immediately by a thick coat, of 3M black velvet paint such that a total coating thickness of 0.002 to 0.003 inch is achieved.

c. After 2 hours of air drying, cover the coated surface with a polyethylene film to prevent the collection of dust particles on the surface.

4. Outgassing - Outgas the fully assembled IR simulator heater zone for a minimum of 4 hours at 250° F at a pressure below 1×10^{-3} torr.

Infrared Simulator Heater-Zone Performance

Several thermal vacuum tests were conducted on full-scale prototype IR simulator heater zones. The coatings previously mentioned were evaluated, using different surface preparation and coating techniques. In addition, several types of controllers, thermocouples, and electrical connections were evaluated. The heatup and cooldown responses of the preproduction IR simulator heater zone are presented in Figure 6. The data are for an isolated heater zone that is not exposed to an external radiation source. The view factor from the spacecraft to the complete 18-zone IR simulator with the 18-inch space between the heater strips and the spacecraft skin is 0.92. The hemispherical emittance of the 3M black velvet paint is between 0.85 and 0.90. Because of the high view factor, the heater strips also were heated by radiation emitted by the spacecraft skin. This effect required that the zones be controlled by temperature instead of by power output. Heating of the heater strips by the spacecraft also caused slower cooling response. However, this effect did not cause any problem of maintaining transient flux conditions during the hot portions of lunar orbit.

The final installation had the disadvantage that the low flux levels required to accommodate the orbital profile of transcending to the dark side of the moon could not be achieved with the simulator in the deployed position. Because the simulator had to be retracted to facilitate the installation and removal of the calibration fixture and the actual test vehicle, the retraction system was designed for cryogenic vacuum service. The results from the full-scale system show that the cooldown response was similar to the prototype data when the simulator was in the retracted position. The flux level at the test article decreased from a maximum of 440 Btu/ft^2-hr to 5 Btu/ft^2-hr in approximately 90 seconds.

CONTROL SYSTEM

The IR simulator was controlled by the acceptance checkout equipment (ACE) computers that are part of the data acquisition and recording system in the MSC Space Environment Simulation Laboratory (SESL). A software computer program was developed to permit either open- or closed-loop control of the 18 power zones to a predefined temperature profile and to provide automated control of the IR simulator lift mechanism for positioning the IR simulator. The computer program generated a 6-bit power signal for each of the 18 power controllers. The details of this program and the general approach to the use of the computer for this application are described in a paper by Dewey (1). The power controllers were silicon-controlled rectifiers capable of producing 12-kilowatt, 117-volt rectified alternating current. The software package provided for considerable flexibility through real-time C-start input of options, including the following.

1. Selection of up to 99 different desired temperature profiles
2. Selection of the time interval between power control signal updates
3. Selection of parameters that regulated the "look-ahead" feature to allow for the thermal response of the heaters to a power change
4. Use of multipliers to modify the desired input-temperature profile for each control zone
5. Definition of thermocouples to be averaged for closed-loop temperature control
6. Definition of lift-mechanism-control parameters
7. Selection of control, timing, and cathode-ray-tube display modes

The IR simulator control sensors were copper-constantan thermocouples mounted on, and electrically isolated from, the heater strips. The thermocouples were arranged in a pattern that provided six thermocouples per heater control zone near the edge of the IR simulator and 12 thermocouples per heater zone near the center of the IR simulator over the open SIM bay on the test article. Any combination of the thermocouples on a given control zone could be averaged and used as the closed-loop control signal for that zone.

The control program read the desired temperature profile recorded on magnetic tape and compared the desired temperature for the current update interval to the measured temperature for each heater control zone. The program then corrected the command to the power controllers to cause the measured temperature to approximate the desired temperature at the end of the update interval. The computer program used a look-ahead feature - based on the difference between the actual and desired temperatures, the length of the update interval, and the physical properties of the heater system - to determine the correction to the power command for each update. At a prescribed time in the profile, the IR simulator could be lowered or raised automatically to provide a step heat input to the test article or to provide a large view of the chamber liquid-nitrogen-cooled cryogenic panels for a low-flux environment.

To provide the data required for the desired-temperature-profile tape, a thermal model of the IR simulator/test-article system was developed. The data required for the profile tape consisted of a set of a desired temperature for each heater control zone for a given update interval that corresponded to a given location in a simulated orbit. The determination of the temperature distribution on the IR simulator heater zones was based on a known flux distribution incident upon the Apollo service module in lunar orbit. The model consisted of 18 planar heater nodes, and 18 corresponding strip nodes on the spacecraft were defined. After determining all of the necessary "script F" radiation exchange factors by using a computerized Monte Carlo technique, a system of 18 simultaneous equations was defined by equating the desired flux for each spacecraft node to the summation of the flux contribution from all heaters. The system of simultaneous equations was solved to determine the required temperature distribution for each update interval. To simulate the equatorial and 45° lunar-orbital environments required for the testing program, the update interval used was 100 seconds, or one update every 5° during the lunar orbit of 2 hours. The starting point for the simulated orbits was defined as the subsolar point, or the center of the dark side of lunar orbit. Approximately 30 minutes after the start of a simulated orbit, the IR simulator was lowered to the proximity of the spacecraft; and, approximately 1 hour later, the IR simulator was raised to simulate the spacecraft passing the terminator to the dark side of the moon.

The simultaneous-equation technique of determining the desired temperature profile was used as a first approximation to be later verified and adjusted during the planned calibration test. The computer program used to solve the simultaneous-equation network also was used to punch cards formatted as required for direct input to the ACE software package. The only significant problem encountered when using this modeling technique was that, during certain portions of lunar orbit, particularly during the 45° inclination orbits, large variations in the required circumferential flux distribution caused the unique network solution to include several temperatures below 0° R. A trial-and-error adjustment of the desired flux distribution was required to correct the network solution to yield a meaningful temperature distribution without significantly altering the resulting flux distribution.

The calibration test data showed that the fluxes incident to the spacecraft both for the equatorial and 45° orbits were approximately 10 to 15 percent higher than those predicted by using the simultaneous-equation network. Because the solution technique did not include reflected and re-emitted energy, this result was expected. Corrections were made in real time during the test by using a C-start input of a multiplying factor for each heater zone, which reduced the desired temperature values by 5 percent. A comparison of the desired flux distribution and the actual flux obtained during the calibration test on a node near the center of the spacecraft for the equatorial orbit is shown in Figure 7, and the same comparison for the 45° inclination orbit for a node near the solar side of the spacecraft is shown in Figure 8.

INFRARED SIMULATOR CALIBRATION

Because the heater strips of the IR simulator are affected by heat emanating from the test article and because, in some locations on the test article, the net flux received at a surface resulted from reflections from several surfaces on the test article itself, the simulator was calibrated with a mockup of the 2TV-2 service module (known as the "boilerplate"), which was outfitted with radiometers. (See Fig. 9.) The radiometer-laden spacecraft scanned the flux profile of the IR simulator, and also of the solar simulation system, as it was rotated 350° about its vertical axis. Details of the calibration phase and the resulting computer direction for programed operation of the system in actual testing were discussed in the previous section. The radiometers employed are of two types. One is the Boelter-type heat-flux transducer, coated with high-emissivity, 3M black velvet paint, mounted directly on the boilerplate spacecraft skin with a continuous-type adhesive (epoxy). The second radiometer is the same type of sensor mounted on a water-cooled (and heated) aluminum block. The water permitted the radiometer to be maintained at constant temperature and was the eventual source of sink of transferred radiation.

The calibration of these radiometers was simple and direct. The technique provided, in a single measurement, an accurate determination of the radiometer sensitivity to incident IR hemispherical radiation in vacuum without the need for an irradiance reference. The radiometers were simply placed in a vacuum chamber, their temperatures were controlled by water flow, and their environments were configured so as to view only black, cryogenically cooled (77° K) surfaces. Because of the radiometer sensing-element design (2), the response is equal in magnitude but opposite in sign for emitted irradiance as compared to absorbed irradiance. Because, according to Kirchoff's law of radiation, hemispherical emittance for a gray body over a given wavelength interval is equal to the hemispherical absorptance for the same interval, the sensitivity of the radiometers for incident hemispherical IR radiation is calculated according to

$$S = \frac{\sigma\left(T^4 - T_w{}^4\right)}{V}$$

where S = radiometer output, Btu/ft^2-hr-mv

σ = Stefan-Boltzmann constant, 0.173×10^{-8} Btu/ft^2-hr-°R^4

T = temperature of the radiometer in the calibration chamber, °R

T_w = temperature of calibration chamber walls, °R

V = radiometer output at temperature T in calibration chamber, mv

It is seen that the flux used for the calibration is that emitted by the radiometer itself to the cold environment, and the only intrinsic parameter that must be accurately known is the radiometer temperature.

The exact value of radiometer emittance is not necessary, provided that the surface is gray in the IR region and is approximately a Lambertian (diffuse) surface in the IR region, as explained in the following.

If the emittance ϵ were known, a calibration factor for absorbed irradiance would be calculated from

$$S^1 = \epsilon S \tag{2}$$

When irradiance is measured, the absorbed irradiance would be determined by

$$\alpha\dot{Q} - \epsilon\sigma T^4 = S^1 \bullet V \tag{3}$$

where V = millivolt output in measurement

α = radiometer absorptivity

$\dot{Q}$ = incident irradiance

ϵ = radiometer emissivity

Because, according to Kirchoff, $\alpha = \epsilon$, the value of $\dot{Q}$ is determined by

$$\dot{Q} = \frac{S^1 \bullet V + \epsilon\sigma T^4}{\alpha} = \frac{\epsilon SV + \epsilon\sigma T^4}{\alpha = \epsilon} = SV + \sigma T^4 \tag{4}$$

and, thus, the value of ϵ disappears in the determination. For the particular type of radiometer employed, the temperature differential between the front face and the rear (reference) face of the slab is much less than 1° F. Therefore, errors caused by differences in measured (body) temperature and sensing-surface temperature are negligible. It has been found that the most accurate temperature measurement is made by silver soldering the measuring thermocouple to the radiometer water line as close to the radiometer as possible, then by wrapping the water line with reflective insulating film. Of course, this procedure requires sufficient water flow. A flow of 0.2 gal/min through 1/4-inch-o.d. line is sufficient.

The radiometers mounted directly on the spacecraft (without water lines) were calibrated in the same manner by mounting them on a plate, the temperature of which was controlled by circulating water. These radiometers had thermocouples embedded in the sensor for temperature measurement. Although this type of thermally nonstabilized radiometer performed as expected during calibration (where heat was supplied by a constant-temperature stream of water), the radiometers gave very spurious data when mounted on the thin spacecraft skin, whereupon the radiometers had to use internal heat content as heat sources and sinks. It is believed that this perturbation of radiometer heat content caused severe thermal gradients within the sensor, which in turn gave the erroneous data, because the sensor measures heat transfer by measuring the temperature differential created by heat traversing its narrow conductive thickness. Such radiometers have been used with success if they are mounted on thick copper blocks, the thermal mass of which essentially dampens the temperature excursions in the radiometer and, thereby, permits it to function properly.

An important factor in the use of the radiometers is that the normal solar absorptance of the 3M black velvet paint is approximately 10 percent higher than the hemispherical IR emittance; and, when radiometers calibrated as described herein are used to measure solar simulation, this difference must be considered in interpreting the data.

CONCLUSION

This IR simulation system also was used successfully to provide the total flux profile incident on the earth-viewing portions of the service module when in earth orbit. It is believed that the techniques described herein may provide solutions to many problems of thermal irradiance simulation in testing articles with varied thermal control surfaces, where diffuse radiation and spectral match is necessary.

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BRN Electrical Engineering Group - Electrical and controller system design

BRN Design Group - Lift mechanism and mechanical design

BRN Environmental Measurements Group - Thermal stress analyses, thermal design and development

NASA TSD - Evaluation and development of coating techniques and heater-zone fabrication

NASA SETD - Design and development of the computer operations controlling the simulation system

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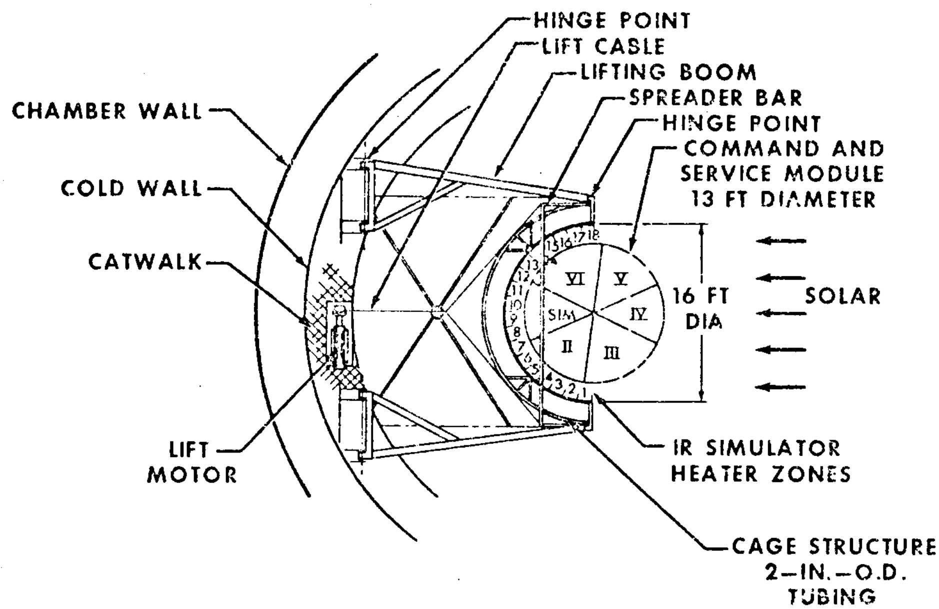

Fig. 1—Infrared simulator lift mechanism

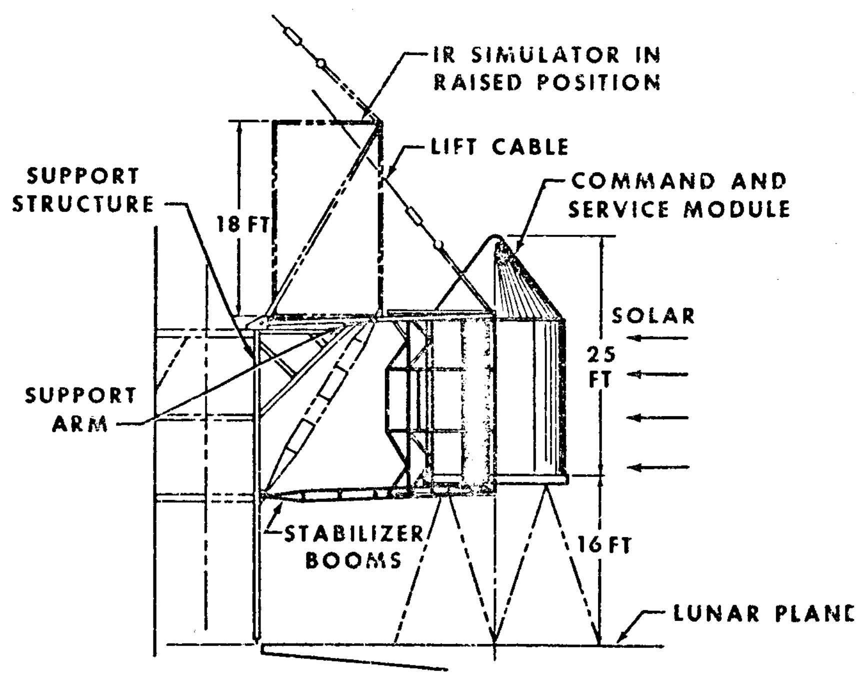

Fig. 2—In-chamber installation of the IR simulator

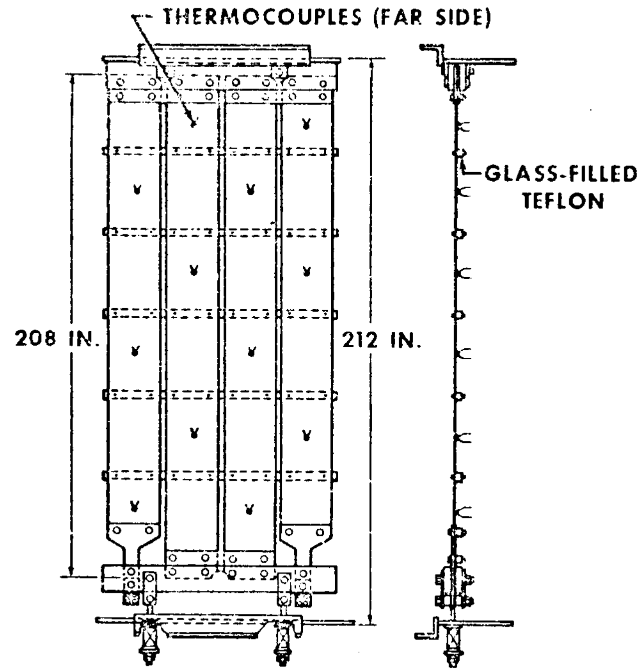

Fig. 3—Typical simulator heater zone with thermocouple installation

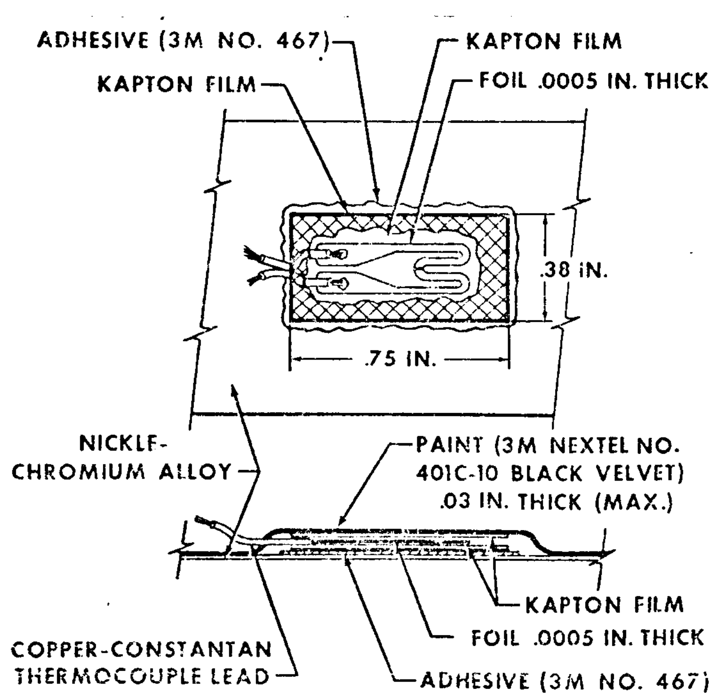

Fig. 4—Thermocouple installation detail

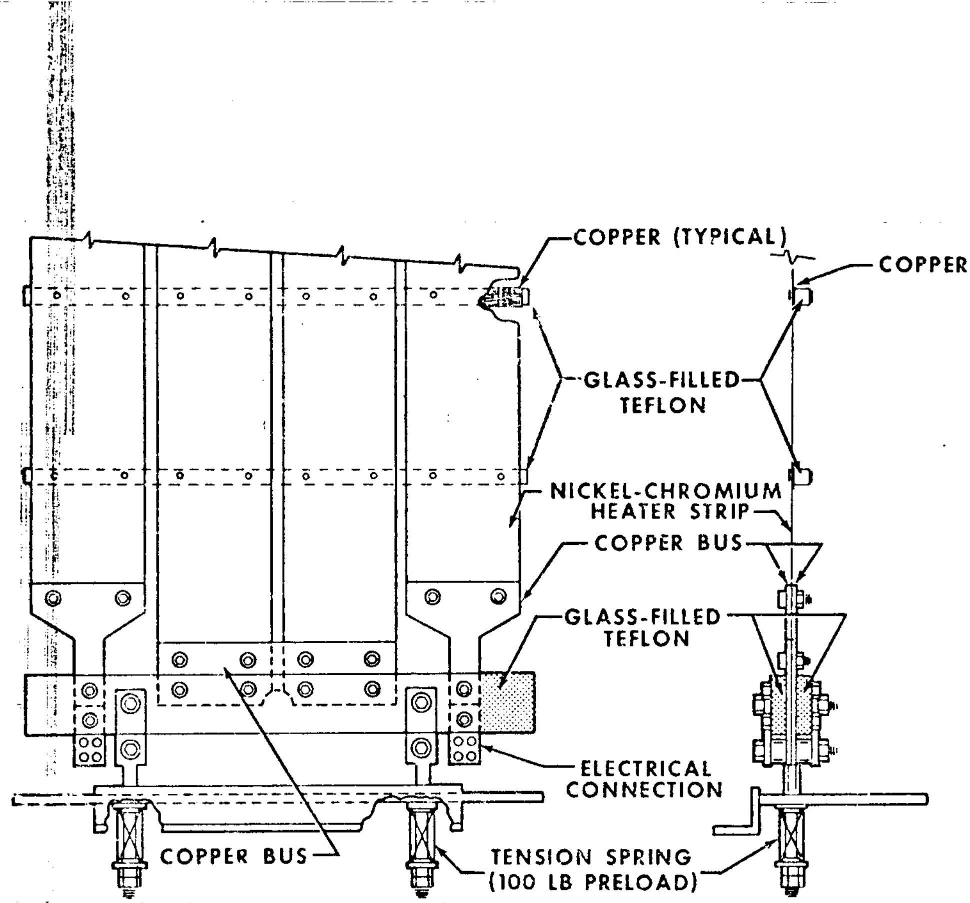

Fig. 5—Infrared simulator heater-zone electrical connection detail

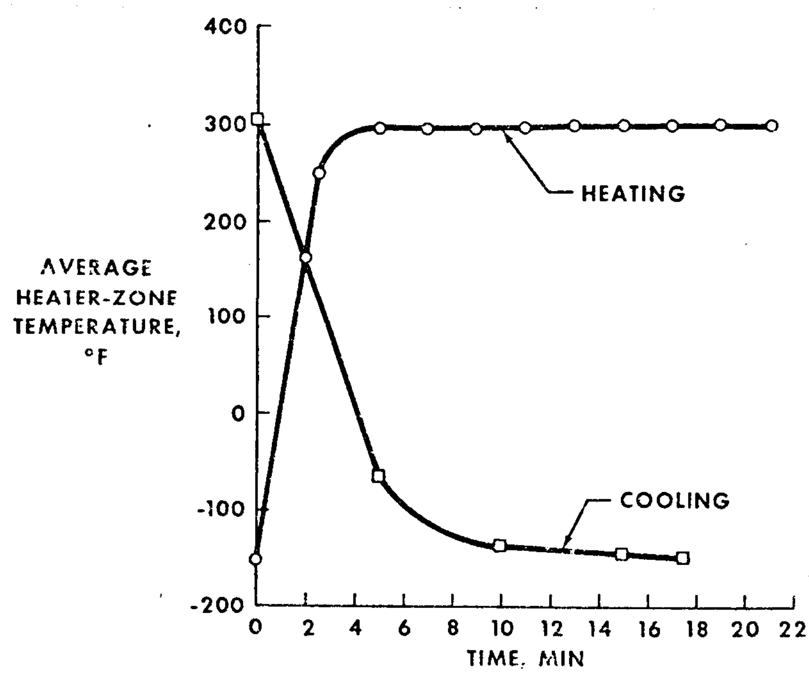

Fig. 6—Thermal response of full-scale prototype IR simulator heater zone

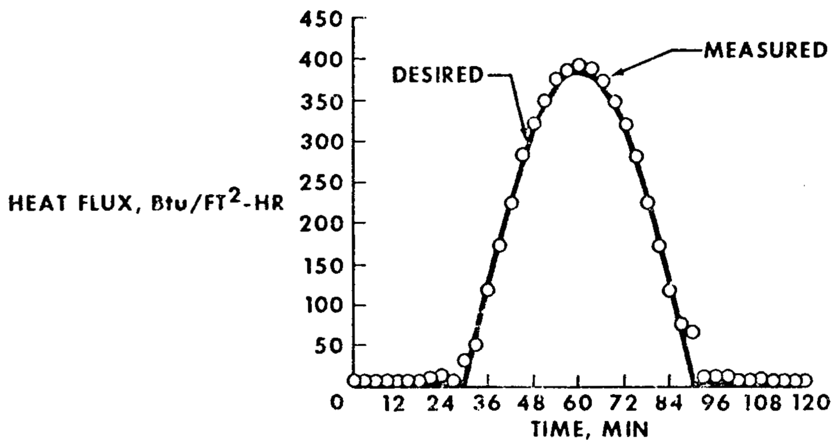

Fig. 7—Comparison of desired and measured flux
(0° orbit, center of spacecraft)

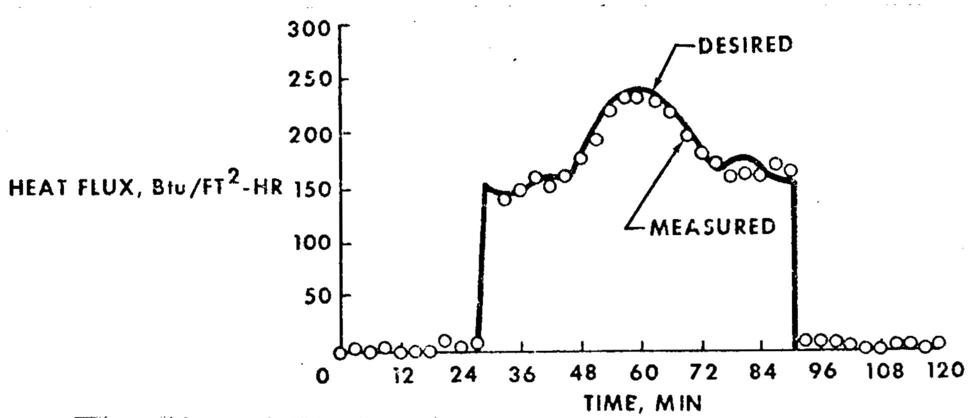

Fig. 8—Comparison of desired and measured flux (45° orbit,
hot side of spacecraft)

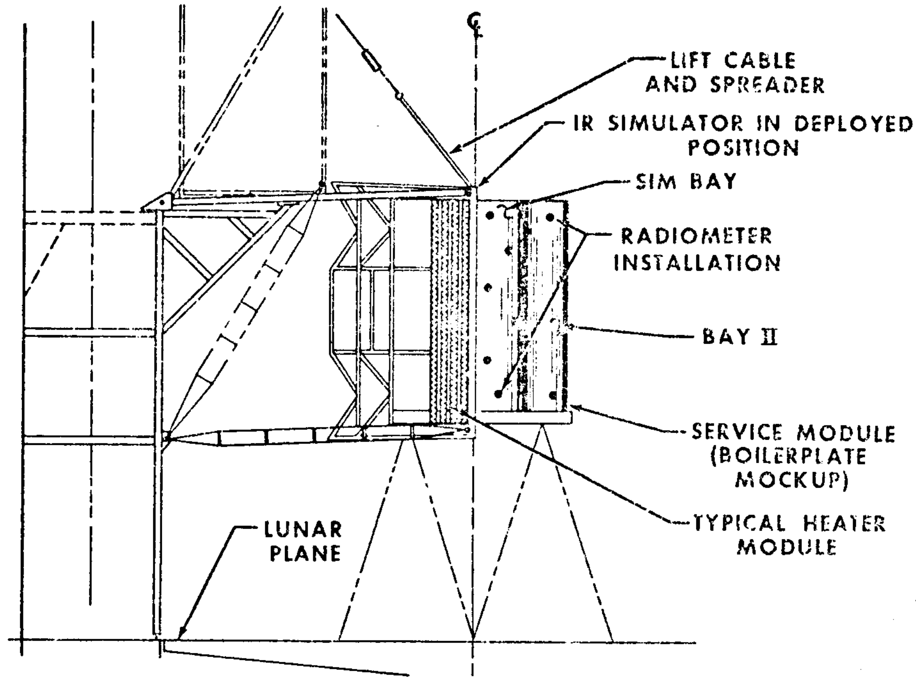

Fig. 9—Calibration system for IR simulator